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Harnessing flexibility potential of flexible carbon capture power plants for future low carbon power systems: Review

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ABSTRACT

Fossil-fired power plants retrofitted with Carbon Capture and Storage (CCS) may have operational benefits for future low carbon power systems. This paper aims to review state of the art literature with the objective to identify whether carbon capture power plants would bring flexibility within future lower carbon power systems. To achieve this objective, at first, the work investigates flexible operation of CCS technology. In particular, flexibility enabling mechanisms and factors that affect the flexible operation of CCS are reviewed. Flexibility requirements and provision assessment tools/metrics for future low carbon power systems are reviewed with the aim to identify the favourite properties required for future low carbon technologies. The work then presents how flexible CCS might improve the conventional power plant flexibility properties. Moreover, the paper presents the value of flexible operation of CCS for different stakeholders while it also identifies different influencing factors of optimal plant operation and profitability. The different power system services that the CCS-equipped plants might serve are also presented.

1. Introduction

Global projections on primary energy demand by fuel source show increases in global fossil fuels use over the coming decades. For instance, the International Energy Agency (IEA) predicts that fossil fuel use is expected to contribute 74% of global primary energy demand by the year 2040 [1]. Additionally, proved reserves of fossil fuels are estimated at 6 trillion barrels of oil equivalent with a reserve to production ratio of 75 years [2]. With all these fossil fuel demand growth coupled with robust reserve availability for fuel use, fossil fuels usage is expected to continue at least in the foreseeable future. On the other hand, the Intergovernmental Panel on Climate Change (IPCC) projections indicate that avoiding the most serious impacts of climate change demands to limit the increase in global average temperature at 2 °C. This sets a global "carbon budget" that has to be met and puts constraint on global fossil fuel use because of their inherent CO_2 emission.

Because of this carbon budget, the electricity industry, which accounts more than 42% of global CO_2 emissions, is subjected to shift to a low-carbon future [3]. Following the landmark climate conference, Paris Agreement, most of the leading developed countries have established or are in the processing of establishing legally binding emission reduction targets [4,5]. For this reason, policy makers should carefully choose the right mix of the future power system generation portfolio that will achieve the de-carbonization targets at the least cost possible. The transitions to low-carbon power systems, in global scale, demands a shift to low-carbon technologies such as renewable technologies, nuclear power and fossil-fuel generators with Carbon Capture and Storage (CCS) [6].

The acceleration of CCS as a mitigation option for CO_2 is even more pronounced, especially within the recently developed context of a more challenging mitigation goal of 1.5 °C compared to the pre-COP21 (Conference of Parties) baseline of 2 °C [7]. Different jurisdictions need to reform power generation so that most optimal pathway of decarbonisation is proportionately decided. On this note, global policy makers consider a pool of genuine measures to combat the emissions of the power generation while maintaining the global economic growth at the least cost situation. Fig. 1 shows the projected estimations of CO_2 reductions expected to be contributed by the different low carbon technologies that are deployable at the moment [8]. Carbon capture power plants (CCPPs) which result from retrofitting existing fossil-fired power plants with CCS technologies is at the forefront of these

Abbreviations: ASU, Air separation unit; CC, Combined cycle; CCPP, Carbon capture power plants; CCS, Carbon Capture and Storage; CO_2, Carbon dioxide; COP21, 21st Conference of Parties; GT, Gas turbine; GW, Giga Watt; HRSG, Heat recovery steam generator; IEA, International Energy Agency; IGCC, Integrated Gasification Combined Cycle; INDCs, Intended Nationally Determined Contributions; IPCC, Intergovernmental Panel on Climate Change; LCPS, Lower carbon power system; Mtpa, Million tonnes per annum; MW, Mega Watt; NGCC, Natural gas combined cycle; NPO, Net power output; ROI, Return on investment; UK, United Kingdom; USA, United States of America; USC PC, Ultra-Super-Critical Pulverised Coal

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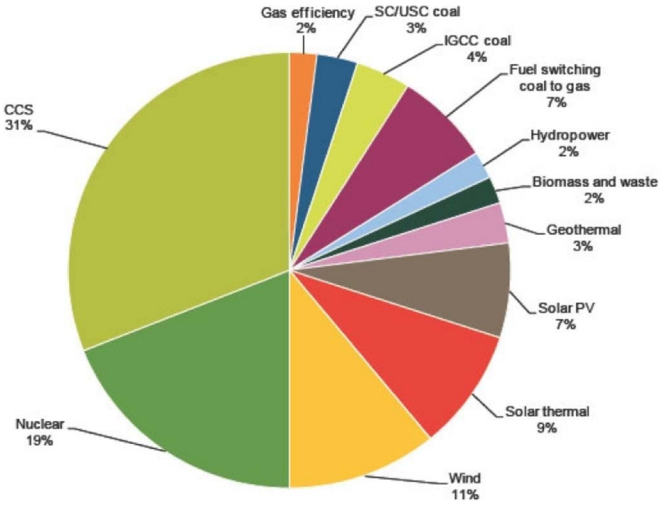

Fig. 1. Contribution of low carbon technologies to reduce power generation CO_2 emissions [8].

measures. At least twelve countries (that includes Bahrain, Canada, China, Egypt, Iran, Iraq, Malawi, Montenegro, Norway, Saudi Arabia, South Africa and United Arab Emirates) have included CCS as a mitigation action within their Intended Nationally Determined Contributions (INDCs) [9].

Recently, researchers have reviewed different aspects of the low carbon power systems including provision of flexibility within several different dimensions of power system contexts (such as the works of [10–13]) and benefits of energy storage technologies [14,15]. Other researchers have reviewed recent developments of different aspects of CCS technologies including efficiency penalties caused by integration of CCS units into conventional power plants [16], techno-economic models of CCS retrofits within power plants [17] and others [18]. While different assessments of flexible operation of CCS within different contexts of power systems have been numerous, there is a gap within literature to conduct a comprehensive review on the value of flexibly-operated CCS within future low carbon power systems.

On the other hand, within the research community of the CCS value chain, there is a general recognition that the CCS landscape, particularly the flexible operation of the CCS, is very different now compared with the beginning of this decade. While there have been many developments (detailed out in Section 2), a comprehensive literature review that critically reviews the existing literature is necessary in order to help in accelerating related research and deployment initiatives.

To this end, this paper aims to identify whether carbon capture power plants would bring flexibility within flexibility-constrained future low carbon power systems. To achieve this objective, the paper first reviews mechanisms of flexible operation of CCS units, presented in Section 3. At Section 4, we investigate the technical requirements that will be present in the future low carbon power systems by conducting a review on flexibility quantification metrics that are recently proposed as new operational tools for power system planning and operations. At Section 5, combination of different flexibility levels are presented. Valuation of flexible operation within power systems is identified from published literature, at Section 6. The paper ends with conclusion section.

2. Carbon Capture and Storage (CCS)

CCS enables continued fossil fuel use for power generation turning the existing infrastructure into clean power sources [19]. Emission from the power generation is the largest application for CCS technologies [20]. Studies show that generation mix with CCS in the portfolio has the ability to provide one of most cost-effective ways of achieving low carbon power generation in the long term such as the case in the UK [21]. Studies conducted by IEA show that over 1000 existing coal-fired power stations which are operating today to be still in operation in 2040. This shows that fuel shifting for low carbon resources does not entirely remove the fossil fired power plants, causing the “carbon lock-in” effect. Besides, total planned new coal-fired power plants alone are estimated by the Global Carbon Tracker study to be around 2440 plants, providing up to 1428 GW, with potential CO_2 emission of approximately 6.5 $GtCO_2$ [22]. The study approximates this number to contribute a percentage share of 16–18% of the total allowed emission in 2030. Without CCS adoption, the global climate goal is either technically impossible or increase prohibitively the decarbonisation costs globally.

However, while CCS has potential of removing significant amount of CO_2, CCS reduces the net power output by 20–30% (7–11% efficiency points) in comparison with those facilities without CO_2 capture [23,24]. A detailed review on efficiency penalty of coal-fired power plants retrofitted with CCS is presented in [16].

2.1. Global planning trends of CCS in power generation

Technical low carbon power planning studies (e.g. [25] and [26]) for different jurisdictions show that CCS offers lower cost option as part of the generation portfolio. For example, the authors in [26] carried out an intensive simulation to quantify and compare the technical and economic performance of power plants for four distinctly different future scenarios with the Netherlands taken as the case study. The authors have highlighted that fossil-fired power plants with CCS will have a large market share in terms of power generation contribution within the generation mix (23–64% of power generated) in the low carbon scenarios. According to simulations in [26,27], estimated prospective of flexibly-operated CCS contribution arises to mitigate the balancing costs incurred as a results of existence of large shares of intermittent renewable sources which present high variability within the future power systems.

On the other hand, initial commercial-scale integrated CCS projects for power plants are beginning to progress towards deployment. Table 1 summarizes the large-scale global CCS projects in the power generation [28]. In the power generation industry, globally, there are two large-scale CCS projects in operation [29,30], with a further one more project under construction [28]. The total CO_2 capture capacity of these three projects is around 5.4 Million tonnes per annum (Mtpa). There are three other large-scale CCS projects that are at the most advanced stage of development planning, with a total CO_2 capture capacity of around 4.5 Mtpa. A further 6 large-scale CCS projects are in earlier stages of development planning and will have an estimated potential of total CO_2 capture capacity of around 10.8 Mtpa.

3. Flexible operation of CCS units

Carbon Capture and Storage (CCS) technologies are CO_2 mitigation option used to contribute the reduction of the CO_2 emission from the power generation and other industries. With capture rates depending on the type of the technology adopted, initial assumptions of the technology operation was to deploy the technology such that it is able to capture consistently the emitted CO_2, leading to full load operation of the facility for most of the time. However, part-load operation, partial capture capability and turn-off options are recently proposed as a mechanism to accelerate the CCS commercialization and adoption at the power generation industry. This phenomena is known as the flexible operation of the CCS.

This review work focuses on the post-combustion carbon capture technologies - Fig. 2 shows schematic diagram of a coal-fired power plant fitted with a post-combustion CCS unit [16]. Post combustion technologies are the most mature technologies among the capture technologies and are currently deployed at a commercial scale [29,30],

Table 1
Global large scale CCS projects implemented in power generation industry [28].

No.	Project name	Location	Project lifecycle stage	Operation date	Capture type	Capture capacity (Mtpa)	Transport type
1.	Boundary Dam Carbon Capture and Storage Project	Canada	Operating	2014	Post-combustion capture	1.0	Pipeline
2.	Petra Nova Carbon Capture Project	USA		2017	Post-combustion capture	1.4	Pipeline
3.	Kemper County Energy Facility	USA	Under-Construction	2017	Pre-combustion capture (gasification)	3.0	Pipeline
Total CO_2 Capture Capacity (Sub-Total)						**5.4**	
4.	Rotterdam Opslag en Afvang Demonstratieproject (ROAD)	Netherlands	Most Advanced Stage of	2019–2020	Post-combustion capture	1.1	Pipeline
5.	Sinopec Shengli Power Plant CCS Project	China	Development Planning	2020	Post-combustion capture	1.0	Pipeline
6.	Texas Clean Energy Project	USA		2021	Pre-combustion capture (gasification)	2.4	Pipeline
Total CO_2 Capture Capacity (Sub-Total)						**4.5**	
7.	China Resources Power (Haifeng) Integrated Carbon Capture and Sequestration Demonstration Project	China	Early Stages of Development Planning	2020's	Post-combustion capture	1.0	Pipeline
8.	Huaneng GreenGen IGCC Project (Phase 3)	China		2020's	Pre-combustion capture (gasification)	2.0	Pipeline
9.	Korea-CCS 1	South Korea		2020's	Post-combustion capture	1.0	Shipping
10.	Shanxi International Energy Group CCUS Project	China		2020's	Oxy-fuel combustion capture	2.0	Pipeline
11.	Caledonia Clean Energy Project	UK		2022	Pre-combustion capture (gasification)	3.8	Pipeline
12.	Korea-CCS 2	South Korea		2020's	Under evaluation	1.0	Shipping
Total CO_2 Capture Capacity (Sub-Total)						**10.8**	
Total CO_2 Capture Capacity (Grand-Total)						**20.7**	

Fig. 2. Schematic diagram of coal-fired power plant with CCS.

with numerous pilot facilities around the World such as Toshiba's pilot facility at Fukuoka [31,32].

3.1. Flexibility-enabling mechanisms

Different mechanisms allow the flexible operation of CCS units, and are generally inspired by the target of regaining the energy penalty lost as a result of diverting energy from the power generation into the operational use of CCS unit. Investigators explore the optimal ability of different mechanisms to allow the power plant to gain back the incurred energy penalty. The amount of energy obtained back at a specific time and its associated speed of response are key distinguishing aspects to consider when proposing a flexibility-enabling scheme for the CCS operation.

There are two main different approaches that enable the flexible operation of a post-combustion type capture technology within the fossil-fired power plants [27,33]. These are (1) constructing a mechanism to allow exhaust flue gas to be vented and (2) addition of solvent storage tanks. Both approaches affect physical structure of conventional power plant facilities. Fig. 3 shows the schematic diagram of the flexibly operated post-combustion capture unit [34].

3.1.1. Bypass (venting)

The easiest and most straight-forward mechanism for introducing flexibility within the CCS is by the use of bypass. This mechanism involves diverting part of the flue gas towards the stack before it enters the CO_2 capture system [35]. Flue gas bypass enables increased power output and reduction in marginal costs by selling the electricity otherwise used for CCS, thereby temporarily increasing [36]. The concept for this feature is to enable the plant to bypass the capture unit when electricity selling prices are sufficiently high for increased generation revenue. In this case, the bypass becomes economically preferable to pay a penalty for emitting CO_2 rather than operating the capture system [33].

3.1.2. Solvent storage tanks

Construction of additional solvent storage tanks within CCS units is another mechanism for introducing flexible operation. This scheme involves redirecting solvent into and out of storage tanks to increase or decrease the net plant output based on economic considerations [35]. The concept for this scheme is to allow absorption process so that CO_2 is removed from the power plant flue gases. The rich solvent is then stored using the storage tank so that the energy intensive solvent regeneration process is left until later time [33].

The advantages of the solvent storage tanks include their ability to permit greater operating profits and lower CO_2 emission than a bypass-enabled flexible capture facility [23]. There is an inherent disadvantage

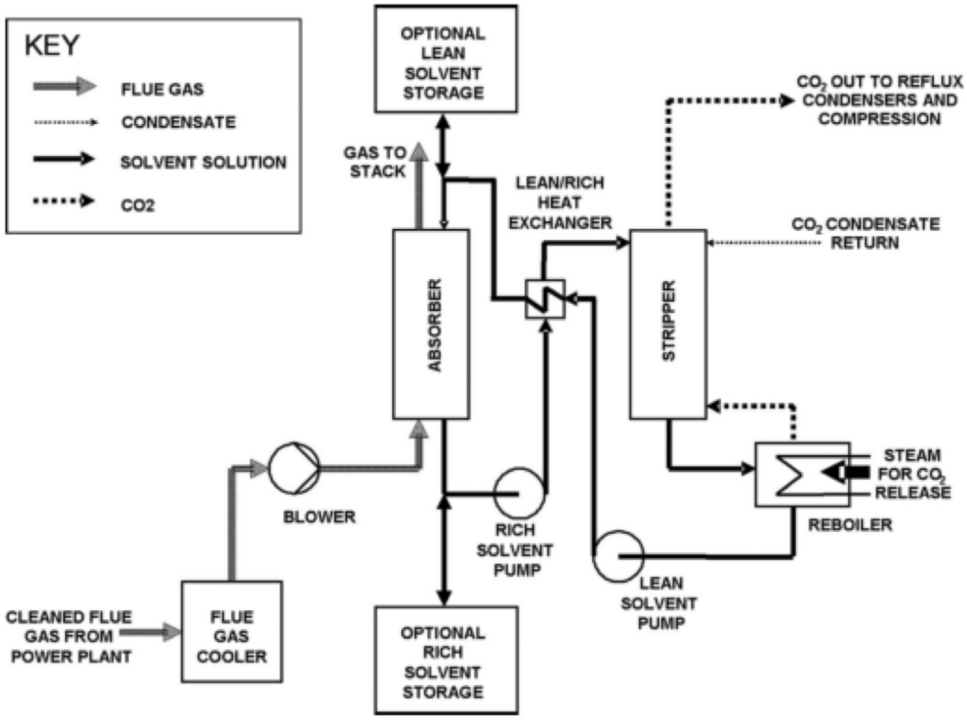

Fig. 3. Schematic diagram of flexibly-operated post-combustion type of CCS [34].

with this scheme which is the capital cost involved in the solvent inventory and storage tanks [23]. This disadvantage may offset the associated benefits of the mechanism. In general, the solvent storage tanks offer significant value that can affect the investment decision of the facility [37].

3.2. Control factors of flexible operation of CCS

Two major factors affect the flexible operation of the CCS units. The first is the volume and the operating strategy of the solvent storage tanks combined, while the second factor is ratio between the loading capability the stripper and that of the absorber columns.

3.2.1. Volume of solvent storage tanks

The ratio between the volume of solvent storage tank and the initial volume of MEA solvent affects the delay time of operating of the subsequent phase (absorption or regeneration). For example, the simulation conducted in [38] assumes two hours of solvent storage under full-load generation operation by making the volume of the storage tank twice more than that of the initial volume of the solvent kept within that same storage tank.

In addition to that, the work of [37] suggests that solvent storage should only be large enough to take advantage of high electricity prices for 15–30 min each day. Besides, simulations presented in reference [25] found out that by increasing the solvent storage capacity from 2-h to 4-h increases the generation from using flexible CCS with solvent storage by up to 50%. As a result, this increases generation revenues by 0.2–0.3 M€ per year. However, the same authors argue that the increase in revenues does not justify the doubling in investment costs for 4-h solvent storage.

3.2.2. Size of stripper

Stripping and compression systems are sized based on the time required to completely fill an empty rich solvent tank at 0% stripper load and 100% absorber load, assuming daily cycling of the storage system [37]. The authors in [38] suggested that the capacity of stripper can be sized to be 25% larger than the capacity of the scrubber. The advantage of this sizing is to allow additional stripping of the stored rich solvent [38].

Researchers in [38] suggest that stripper capacity should be oversized in relation with the size of the absorber in order to allow higher stripping rate during flexible operation. However, the authors in [37] found out that the capital costs of larger stripping and compression equipment are significant. This is an important message for the investors of the technology to consider during the design and implementation stage of these facilities. On the other hand, a recent study [36] found out that oversizing the regenerator for the purpose of flexibility is unlikely to be economic. This is in contrast to the assumptions made in much of the work on the topic of flexible CCS.

4. Power system needs for generation flexibility

High shares of intermittent renewable power sources are expected to be deployed within future power systems [39]. The resultant systems are characterized with steeper ramps (rate of increase or decrease in dispatchable generation to follow changes in Netload), deeper turn downs (operation of dispatchable generators at low levels), and shorter peaks (periods where generation is supplied at a higher level) in system operations [40]. Peaks are shorter in duration, resulting in fewer operating hours for conventional plants, affecting cost recovery and long term security of supply [40].

In this context, the significance of the need for more system flexibility becomes directly proportional to the penetration level of variable generation within a specific power system. Power system flexibility can be defined as system's ability to rapidly respond to fluctuations with controllable real power resources [41]. These fluctuations are large, frequent and rapidly changing. Without enough flexibility, the penetration of variable generations may be limited in order to ensure the reliability of the bulk power system [42]. As power systems evolve to incorporate more renewable energy, regulators and system operators are recognizing that flexibility across all elements of power systems must be addressed. Fig. 4 shows different types of intervention mechanisms to address the flexibility needs of a particular power system [40]. The interventions are ranked according to their

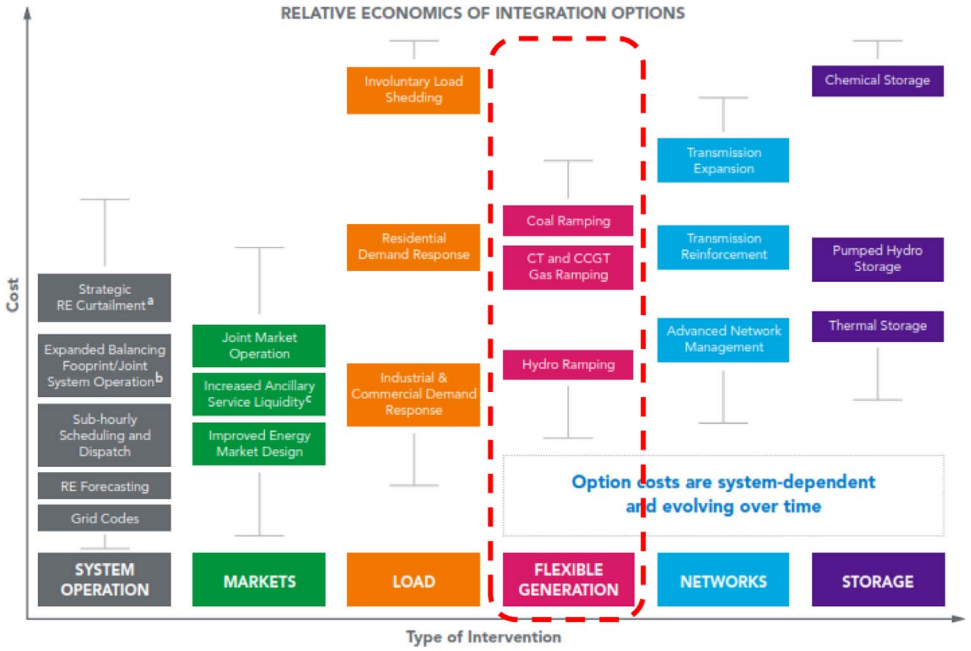

Fig. 4. Intervention mechanisms for power system operation.

associated costs.

It is beyond the scope of this work to provide a comprehensive review of flexibility requirement (as presented in [43]) and/or flexibility provision mechanisms (as presented in [11]). Other comprehensive reviews are presented in [44,45], for which the reader can refer for more understanding on the topic. Since the aim of this work is to investigate the potential benefits of flexible operation of CCS, a technology that affects the operation of power plants at the supply side of the power grid, this section focuses on the provision flexibility from the supply side only. The content obtained from this literature is then mapped to justify the ability of the flexibly operated CCS to contribute the flexibility provision schemes available for future low carbon power systems.

Supply-side flexibility, particularly, flexibility within power generation sources, are the main sources of flexibility providers and they are usually contracted to provide regulating energy (spinning reserves) or are able to be redispatched sufficiently fast (manual reserves) [46]. On top of that, some of proposed low carbon technologies present further need for more options of flexibility. Two major potential energy production contributors are wind and nuclear [47–49]. Both of them are inherently non-flexible and/or introduce increased variability and uncertainty within systems. Therefore, the burden of providing system balancing activity falls to the fossil-fired power plants. Even for these plants, gas-fired is prominent in providing system flexibility [50]. However, an excessively increased interconnection between electricity networks and gas infrastructure leads to energy security concerns [51]. This has triggered a new research in developing integrated optimization models of electricity and gas networks (such as the works presented in [52] and [53]), in order to increase the reliability and security of these important energy networks.

To this end, a portion of the system flexibility is also expected to be provided by existing and/or planned fossil-fired power plants. However, many of these power plants are designed and constructed in such a way that they are operated as baseload generators, such as the Ultra-Super-Critical Pulverised Coal (USC PC) and Integrated Gasification Combined Cycle (IGCC) power plants [54]. Therefore, by designing flexible operated CCS units is expected to bring in further flexibility to fossil-fired power plants.

4.1. Identification of power plant flexibility parameters

Different flexibility resource characteristics are available within different power generation facilities. In order to understand type of plant characteristics needed for system flexibility support, this subsection reviews metrics and tools used to assess flexibility requirements and its provision within a particular power system. Recent researchers have taken various different approaches in order to develop tools and techniques that help stakeholders of the power system planning and operations. Table 2 investigates the type of flexibility characteristics related to the power generation facilities that different tools incorporate into their assessment methodologies.

The development of the various different tools is inspired by the type of target application and/or intended users for its eventual use. For example, the works in [55,56] are intended for diverse audience including non-technical experts such as journalists, investors and policy makers. Therefore, visualization-based methods are appropriate for providing quick-understanding of flexibility and in comparison with different countries/jurisdictions or geographical regions. On the other hand, tools used for daily system operations and planning can be take several forms. Index-based tools such as the Insufficient Ramping Resource Expectation (IRRE) [57,58] and the Lack of Ramp Probability (LORP), provide a snapshot of system flexibility needs in the short term planning horizon (e.g hours to days). As the field of flexibility advances quickly, recently researchers have also proposed more advanced and comprehensive flexibility valuation and provision tools such as the works presented in [64–67]. Many of these comprehensive mathematical models are capable to be incorporated with existing system operation computations and algorithms, used in day-to-day basis.

Because of these different forms and categorization of tools available, the parameters used for flexibility are overlapping, when compared against each other. For example, the chart in [55] considers dispatchability as a parameter of power plant flexibility, while that can be quantified in a more precise and accurate way by using ramp rates (rates of power plants to decrease/increase plant output), power capacity (ability to lower minimum and/or maximum power generation levels) and minimum and shut down times as presented in [67]. Other distinguishable important parameters are cycling ability and multi-fuel capabilities of the power plants as captured in [56]. Researchers

Table 2
Flexibility parameters available at different power plant considered for different valuation metrics.

No	Metric name	Form of proposition	Target application (planning horizon)	Method classification	Types of users	Flexibility parameters considered	Ref.
1.	Flexibility Chart	Chart	Long term system planning	Visualization Methods	Policy Makers (Non-Technical)	Dispatchability and Power capacity	[55]
2.	FAST2 Method	Chart				Power capacity, Multi-fuel capability, and Cycling ability	[56]
3.	IRRE	Algorithm (Set of steps to finally come up with a value)		Indices (as Flexibility Metrics)	Power Plant and System Operators	Ramp rate	[57,58]
4.	N/A	Deterministic Formula (Offline Metric)				Ramp rate and Power capacity	[59]
5.	N/A	Mathematical Characterization (Differentiation and Integration)	Short term operational planning			Ramp rate, Power capacity and Energy capacity	[60–62]
6.	LORP	Probability-based Tool				Ramp rate and Power capacity	[63]
7.	Dynamical Envelope	Mathematical Optimization Formulation and Trajectory Tracking & nth Order Dynamics		Comprehensive Mathematical Models		Ramp rate and Power capacity	[64]
8.	Flexibility Envelope	Mathematical Representation of Flexibility Envelopes				Ramp rate and Power capacity	[65]
9.	N/A	Modification of Objective Function				Reserve capacity and Ramping rate	[66]
10.	N/A	Unit Clustering-based Method				Startup cost, Power capacity, Ramp rate, Minimum up/down times, Operating reserve capabilities,	[67]

specializing in short term planning time frame computational tools do not include these two broad parameters as part of the valuation for system and/or plant flexibility capabilities such as the works in [60–62,64–67].

5. Improvement of power plant flexibility by flexible CCS

From the previous section, several important flexibility valuation parameters are identified based on the current state-of-the-art flexibility assessment tools. These include: capacity range, ramp rate, reserve capacity, startup cost, minimum up/down times, ability to dispatch the facility, multi-fuel capability and cycling ability of power plants. In this section, how flexible CCS to enhance some of these power plant flexibility parameters is presented.

In terms of power capacity range, integration of flexible CCS into the power plant does not introduce major change to the maximum generation limit, as long as the post-combustion technology is able to independently turn off when needed. There is permanent basic efficiency loss at the power plant that results from CCS integration [38,68]. But this basic efficiency penalty is negligible for tangible plant operations purposes [38,69]. On the other hand, operating the CCS to a certain level when at the same time operating the power plant at the minimum generation limit leads to further lower limit of power output from the resultant CCPP unit. This argument is theoretically presented in [68,69]. While the capture plant can reduce the minimum load further, estimates presented in other studies [26,70] suggest that at different jurisdictions with different emission standards, the minimum load might be set by the emission regulations as opposed to the operation of the plant at the minimum generation output. This is due to considerable emission level increase of power plants when operated at low load levels. In contrast, some field studies [26,70,71] suggest that CCS does not affect the minimum load level of the basic power plant. This is achievable as long as the parallel compressor trains are present [26].

In regard with other flexibility parameters, Table 3 summarizes the key flexibility features of the power plants with and without CCS, so to point out the impact of the CCS to the power plant [54]. This summary is based on a work IEA Greenhouse Gas R & D Programme (IEA GHG) commissioned to Foster Wheeler to perform a study that assesses the potential flexibility of certain power plants equipped with CCS units [70]. Two of the investigated coal- and natural-gas-fired power plants were natural gas combined cycle (NGCC) and ultra-super-critical pulverised coal (USC PC) power plant. Both of these plants were equipped with post-combustion capture.

Another important flexibility parameters that is useful for policy makers includes ability to install separately-controlled multi-capture installations for large power plant [72]. With large power plants whereby several turbine generators are available, different capture systems can be installed separately. This improves the flexible operation of the whole facility by increasing the control parameters further.

5.1. Combining flexibility perspectives

There are three levels of flexibility involved when considering the whole systems approach of the power systems. These are: (1) *CCS level flexibility* which allows ability to control levels of operation of CCS units, (2) *Plant level flexibility,* which allows the ability to decouple emission and generation outputs, that allows plant operators to efficiently maneuver between CO_2 and electricity prices, optimizing the plant revenue, and (3) *System level flexibility*, that allows more accommodation for variable renewable energy sources, leading to the reduced associated curtailment cost. Combining these different levels of flexibility helps to understand the flexibility degrees of the power plant within the power system perspectives. Fig. 5 shows the different flexibility levels and issues of importance for operations at each level.

At the CCS level, not only the power grid operation benefits of the

Table 3
Flexibility parameters of power plants with and without CCS.

Plant configuration	Turndown	Cycling capability Start-up to full load	Ramp rates
NGCC	Low load operation: 15–25% CC load (10–20% GT load) Min. environmental Load: 40–50% CC NPO (30–40% GT load)	Hot start-up: 45–55 min Warm start-up: 120 min Cold start-up: 180 min	35–50 MW/min max Hot start-up load change rate: ● 0–40% GT load: 3–5%/min ● HRSG pressure: 1–2%/min ● 40–85% GT load: 4–6%/min ● 85–100% GT load: 2–3%/min
With CCS	Post-combustion unit min. load: 30% CO_2 compressor min. efficient load: 70%	Regenerator preheating: ● Hot start-up: 1–2 h ● Warm start-up: 3–4 h	Same as plant w/o CCS
USC PC	Min. boiler load: 25–30%	Very hot start-up: < 1 h Hot start-up: 1.5–2.5 h Warm start-up: 3–5 h Cold start-up: 6–7 h	30–50% load: 2–3%/min 50–90% load: 4–8%/min 90–100% load: 3–5%/min
With CCS	Post-combustion unit min. load: 30% CO_2 compressor min efficient load: 70%	Regenerator preheating: ● Hot start-up: 1–2 h ● Warm start-up: 3–4 h	Same as plant w/o CCS

flexible CCS is important (which are detailed in Section 6.3.), but also the CO_2 downstream network considerations. Flexible operation of CCS leads to variable use of transport and storage facilities, which are mostly yet to be built. The costs caused by these variabilities need to be quantified and CO_2 networks should be pre-designed to accommodate these CO_2 flow variations. It is noteworthy that variability in the supply of CO_2 will reduce the utilization rate of transport and storage, increasing the costs per tonne of CO_2 stored [73]. Moreover, the use of solvent storage (as discussed in Section 3.1.2.) will increase the peak CO_2 flow that these facilities must be able to process, which may also increase transport and storage costs [25].

6. Value of flexible operation of CCS

A key factor that quantifies the benefits of flexible operation of CCS is the controllability of the energy demand of the capture unit. The extent of this controllability determines the reduction in net power output of the basic power plant [25]. Table 4 summarizes the different technical studies conducted in order to assess the extent of value that flexible operation of CCS might bring to the plant or system operators [35]. The two major issues that are proven in different literature include the increase of return of investment and the technical feasibility of incorporating flexibility within the CCS systems.

6.1. Stakeholder perspectives

Different stakeholders within the value chain of the power systems have different interests at stake for flexible operation of the CCS. Power utility companies, national grid operators, which are mostly non-profit making bodies, and national and/or regional policy makers are three key stakeholders that have the responsibility of ensuring efficient and sustainable way of operating the power systems at each jurisdiction. Table 5 presents examples of some of concerns of these stakeholders showing the differing perspectives (roles) of valuing flexible operation of CCS facilities [33].

Table 4
Flexibility studies for Mono Ethanyl Amine-based post-combustion CO_2 capture at coal-fired power plants.[a]

Ref.	Study type	Benefits of flexible operation
[23]	Storage and Bypass Assessment	Flexibility may increase ROI
[37]	Storage and Bypass Assessment	Flexibility may increase ROI
[34]	Screening of Flexibility Options	Flexibility is likely valuable
[74]	Dynamic Absorber Simulation	Model useful for operability studies
[75]	Pilot Plant Operating Data	Flexibility is technically feasible
[76]	Storage and Bypass Assessment	Flexibility may increase return of investment (ROI)
[77]	Storage Assessment	Storage may increase ROI
[78]	Storage Assessment	Storage may increase ROI

[a] IGCC+CCS with syngas storage has also been explored, indicating that storage could increase ROI.

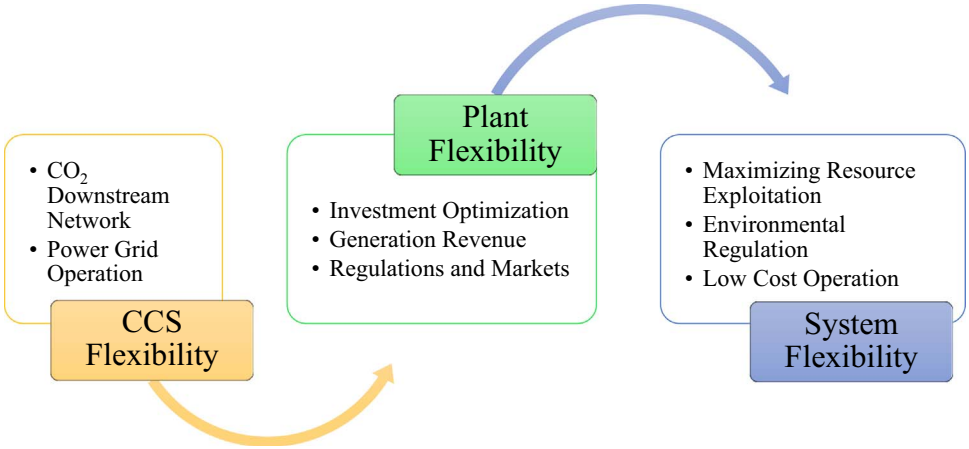

Fig. 5. Combining flexibility perspectives at different levels of the power grid and issues of consideration at each level.

Table 5
Potential concerns of certain stakeholders interested in flexible operation of CCS [33].

Stakeholder	Example role	Example concerns
Independent Power Producer	Own and operate power plants to make a profit.	1. Managing a portfolio of plants that leave options open given an uncertain future. 2. Maximizing value of plants within portfolio (e.g. by selling electricity, grid support services, any useful by-products).
Grid Operator	Operate electricity network and responsible for ensuring reliable, high quality electricity supply.	1. Providing secure supply at minimum cost (e.g. by identifying generators or consumers that are able to operate flexibly to minimize peaks in prices).
Policy-makers	Responsible for protecting society's interests, e.g. by making laws and determining incentives.	1. Introducing legislation to protect the environment. 2. Identifying most cost-effective approaches to shape decisions so that benefits to the society is maximized.

Table 6
Sensitivity factors that influence the flexible operation of CCPPs.

No.	Factors	Market	Ref.	Findings of the study
1.	Electricity Prices	Power	[25]	• All else being equal, a plant with sufficient flexibility to maximize output when electric energy prices are high and minimize output when prices are low will be more profitable than an inflexible unit.
			[35]	• Price differences drive the value of flexibility, with a profit-maximizing operator choosing to store rich solvent during periods of high prices and regenerate extra solvent during periods of low prices.
			[33]	• The ability of a CCPP plant to bypass a capture unit is likely to be valuable when electricity selling prices are 2–3 times higher than the $/tCO$_2$ penalty for emitting CO$_2$.
2.	CO$_2$ Prices	Carbon	[37]	• Benefits of venting diminish at high CO$_2$ prices, but a solvent storage system that permits high CO$_2$ absorption during partial-load stripping and compression achieves a 9–29% profit advantage at 30–100 USD/tCO$_2$.
			[23]	• Economic benefits are greatest at low CO$_2$ prices where CO$_2$ capture investment might still be unjustifiable. • Flexibility provides the greatest economic advantage if CO$_2$ prices are 40–50 t/CO_2$ for substantial portion of plant economic life.
			[36]	• Flexible CCS increases profitability by 0–35% depending on CO$_2$ prices. Value of flexible CCS decreases with CO$_2$ prices. • CO$_2$ prices are high enough to swap the position of some units in the dispatch curve.
			[25]	• Changing CO$_2$ price influences the power plant generation, reserve provision and electricity generation revenues. Both power generation and revenues of the power plants with flexible CCS decrease in case of a lower CO$_2$ price as result of the power plant is moving to a later position in the merit-order and lower electricity prices. The shift in merit-order dominates the impact of lower CO$_2$-price.
3.	Gas Prices	Energy (Gas)	[79]	• The cost and reliability (ancillary) service benefits of flexible capture are found to increase with CO$_2$ and natural gas prices because units become more economical to operate.
4.	Fuel Prices in combination with CO$_2$ Prices	Energy and Carbon	[25]	• Results obtained for both fuel price and CO$_2$ price sensitivities are similar. The only exception is that change in fuel prices affects the generation revenues of venting generation, which are 10 M€ higher in the 'low CO$_2$ price and high fuel price' case compared to the base case because of the higher electricity price-levels.

6.2. Influencing factors of optimal plant operation and profitability

Within the recent literatures, several important factors have been investigated by various researchers. Different factors lead to different benefits on system-wide operations. Table 6 summarizes recent literatures that have explored different sensitivity factors that affect the flexible operation of the CCPPs. Findings reviewed studies related to the factor investigated is listed in the Table.

6.3. Provision of power system services

The flexible operation of the CCPPs helps the system operator to vary power plant's electrical output which brings in three folds of benefits. These are maintaining grid reliability, contributing to meet the peak demand and improving profitability when electricity prices are high. Literature shows that flexible operation of CCPPs provides considerable benefits [34,80] for low carbon power systems. The potential power system services that CCPPs might offer are summarized in Table 7.

7. Conclusion

Retrofitting fossil-fired power plants with CCS has two advantages. Firstly, the CCS is one way to avoid turning the existing and/or planned fossil-fired plants become "stranded" assets. Secondly, CCS retrofits have the potential to transform the operational characteristics of the plants without the need to build new flexible generation plants. Focusing on the latter, the transformed plants allow the system operator to operate the facility with a range of options for grid support services. This may include provision of flexibility needs of the systems and decoupling emission and generation output for better adjustment between electricity and carbon markets. The flexibility arises due to the controllability of CCS operation. This paper presented a comprehensive literature review addressing the potentiality of harnessing flexibility potential of flexible CCPP for future low carbon power systems. The objective of the work was to investigate whether the flexible operation of the CCPPs can provide needed power system flexibility in future low carbon power systems. The review work reveals several issues that will be useful for future studies and engineers on the field. These include: (1) flexible operation of CCS and the different factors and issues that need to be considered for appropriate studies or design, (2) identification of flexibility parameters (this research work reveals some of the latest information about the flexibility metrics), (3) flexibility perspectives ranging from CCS level, to power plant level, up to the system level, (4) Factors that affect optimal plant operation and profitability, and lastly, (5) services that flexible operation of CCS is able to deliver in the context of power system operations. These issues help the business case and the understanding of the capture technology within the stakeholders of the power system operations sector. It particularly provides a knowledge support the different power system community members such as the system operators, day-to-day system planners, technical and academic researchers involved in this field.

Table 7
Services provided by flexible operation of CCS.

No.	Services	Market	Ref.	Findings of the study
1.	System Demand (or Netload)	Power	[33,81]	● Flexible operation allows variability of the energy penalty incurred as a result of operating the stripper. This can be achieved by storing the rich solvent during peak load period and regenerating it later in off-peak period. This postpones the energy penalty incurred as a result of operating the stripper column.
2.	System Costs	Power	[79]	● Flexible operation is found to reduce electricity dispatch costs by responding to variability in electricity demand.
3.	Spinning Reserve	Power	[82]	● The authors found out that the operating status of the CCPPs have a significant effect on the overall cost and on the spinning reserve requirements. The results also show that CCPPs can play an important role in spinning reserve provision.
			[79]	● Given sufficient system response time, the ability to reduce capture load (energy requirement) allows facilities to provide substantial low-cost reserve capacity, and units with capture operating below 100% load can offer the ability to increase capture load for unexpected increases in supply such as from wind.
			[25]	● Flexible CCS can provide a large share of the Netherland's reserve capacity (over 17%) by the year 2020.
				● The main benefit of flexible CCS is an increase in reserve capacity provision by the power plant of 20–300% compared to non-flexible operation.
4.	Dispatchability: (Emission and Economic Dispatch)	Power and Carbon	[69]	● Incorporates independent emission dispatch capability within the traditional economic dispatch models. The authors found out that independent dispatch between emission and generation reduces the total system costs and the CO_2 emission.
5.	Synergy with Energy Storage	Power	[79]	● The existence of grid-scale energy storage does not significantly detract from the value of flexible capture.
6.	Wind Curtailment	Power	[69]	● Reduces the amount of curtailed wind.

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